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Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale

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SUMMARY

Biofiltration systems are a recommended and increasingly popular technology for stormwater management; however there is a general lack of performance data for these systems, particularly at the field scale. The objective of this study was to investigate the hydrologic and pollutant removal performance of three field-scale biofiltration systems in two different climates. Biofilters were shown to effectively attenuate peak runoff flow rates by at least 80%. Performance assessment of a lined biofilter demonstrated that retention of inflow volumes by the filter media, for subsequent loss via evapotranspiration, reduced runoff volumes by 33% on average. Retention of water was found to be most influenced by inflow volumes, although only small to medium storms could be assessed. Vegetation was shown to be important for maintaining hydraulic capacity, because root growth and senescence countered compaction and clogging. Suspended solids and heavy metals were effectively removed, irrespective of the design configuration, with load reductions generally in excess of 90%. In contrast, nutrient retention was variable, and ranged from consistent leaching to effective and reliable removal, depending on the design. To ensure effective removal of phosphorus, a filter medium with a low phosphorus content should be selected. Nitrogen is more difficult to remove because it is highly soluble and strongly influenced by the variable wetting and drying regime that is inherent in biofilter operation. The results of this research suggest that reconfiguration of biofilter design to manage the deleterious effects of drying on biological activity is necessary to ensure long term nitrogen removal.

Introduction

Widespread recognition of negative impacts of urban stormwater (Hatt et al., 2004; Leopold, 1968; Meyer et al., 2005) has resulted in the identification of two important related goals for its management, that is, maintaining stormwater quantity (flood peak and total volume) and quality (pollution) as close to pre-development levels as possible. A range of stormwater treatment technologies have been developed in response, for example, stormwater wetlands, sedimentation ponds, sand filters, infiltration systems and, more recently, biofiltration systems (e.g. Davis, 2005; Wong, 2006).

Biofiltration systems (also known as biofilters, bioretention systems, and rain gardens) operate by filtering diverted runoff through dense vegetation followed by vertical filtration through soil filter media. Treatment is achieved via a number of processes including sedimentation, fine filtration, sorption, and biological uptake (PGC, 2002). Water is then collected in under-drains at the base of the filter media for discharge to receiving waters or storage for reuse. Biofilters are receiving increasing interest due to their design flexibility, small footprint, and landscape improvements, such as aesthetic enhancement. However, to date, performance data for biofilters have generally been limited to the laboratory-scale, with few studies reporting on field-scale testing (Dietz and Clausen, 2005).

Past studies generally report high retention of sediment, heavy metals, and phosphorus, but variable removal of nitrogen, particularly nitrate. Laboratory studies conducted by Davis et al. (2001, 2003, 2006) demonstrated effective reductions in concentrations of heavy metals (>90%, 2003), phosphorus (70–85%, 2006) and ammonium (60-80%, 2001), but variable removal of nitrogen (15-65%), largely due to poor retention (<20%) and frequent leaching of nitrate (2006). Henderson et al. (2007) tested the treatment performance of three different filter media (gravel, sand, and sandy loam) in vegetated and non-vegetated columns. They found that the vegetated columns removed 63-77% of nitrogen and 85–94% of phosphorus loads, but the non-vegetated columns were shown to leach nitrogen. Hatt et al. (2007b) also reported leaching of nitrogen and phosphorus in their column study of non-vegetated filter media. In a very recent, large-scale laboratory study, Fletcher et al. (2007) investigated the influence of filter media and vegetation selection on pollutant removal and found that sediment concentrations were consistently reduced by at least 96% and phosphorus by an average of 80% for all design configurations.

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Nitrogen removal was much more variable and ranged from a net increase to 70% reduction in nitrogen concentrations (Fletcher et al., 2007). The selection of vegetation was found to play a critical role in determining nitrogen removal performance.

At the field scale, far fewer studies have been undertaken. Davis et al. (2006) assessed the treatment performance of two field sites using only one simulated storm event at each site, and reported good reductions in phosphorus (65–87%) and moderate reductions in nitrogen (49–59%) concentrations, but poor removal of nitrate (15%). They also showed very good reductions in heavy metals concentrations at one site (>95% removal of Zn, Cu, and Pb), and moderate removal rates at the second site (43%, 70%, and 64% removal for Cu, Pb, and Zn, respectively, Davis et al., 2003). In another field study, three storm events were monitored, and while load removal rates in excess of 98% were consistently reported for Cu and Zn, removal of nitrogen and phosphorus varied according to the season, with good removal of phosphorus (51%) and nitrogen (89%) loads reported in the summer, but significant leaching of both in winter (Hunt, 2003). However, it should be noted that all these studies reported results from a very small number of events, of which some were simulated.

Research to date has generally focussed on the pollutant removal performance of biofilters, with less attention given to their hydrologic performance. Biofilters have previously been thought to have little water quantity control benefit and provide only minor flood control benefits (ARC, 2003; Melbourne Water, 2005), with little empirical data or even modelling to support this assumption. Hunt (2003) studied a field scale system and observed a seasonal difference in outflow volumes, with significantly reduced outflow relative to inflow in the summer, but a less pronounced reduction in runoff volumes during winter (the total outflow volume in the summer monitoring period was 13% of that observed in winter, where approximately equal rainfall occurred in each monitoring period). Hunt attributed these losses to be primarily via exfiltration into the surrounding soil, however this is a hypothesis, since the contributions of exfiltration and evapotranspiration to flow reduction could not be differentiated.

This paper reports on the findings of three separate studies of field-scale biofiltration systems in Australia that were conducted to close the gap in our knowledge of hydraulic and treatment performance of these highly popular stormwater treatment systems. We use flow and water quality monitoring to quantify retention of flow and pollutant and load reductions by biofiltration systems. We then assess the influence of flow on pollutant removal as well as the variability in effluent pollutant concentrations relative to stormwater. The key finding is that although their performance is very variable (depending on the design characteristics), biofiltration systems are a promising technology for restoring both predevelopment hydrology and water quality.

Methodology

Site description

Monash University

The first field site was a biofiltration basin treating runoff from a multi-storey carpark at Monash University, Clayton campus, Victoria (Fig. 1). This system was constructed in late 2005 and is the second stage in a two-stage treatment train (two sedimentation tanks are the first) draining a 100% impervious carpark with an area of 4500 m^2. Below-ground, the biofilter filter media were divided into three separate cells by concrete barriers (each 1.5 m wide, 10 m long and 0.7 m deep (500 mm soil filter media plus a 200 mm drainage layer); 1% of the catchment area in total), each containing a different filter media: Cell 1, sandy loam (SL); Cell 2, 80% sandy loam, 10% vermiculite, 10% perlite (SLVP), by volume; Cell 3, 80% sandy loam, 10% compost, 10% hardwood mulch (SLCM), by volume. Each cell contained a dense growth of native sedges and rushes: *Carex appressa, Carex tereticaulis, Lomandra longifolia, Isolepis nodosa, Caleocephalus lacteus*, and *Juncus* spp. An overflow weir allowed water to pond to approximately 250 mm (the barriers between filter media did not extend above ground level, so water ponds uniformly across all three cells). Perforated 100 mm diameter PVC pipes were located in the drainage layer of each cell to collect the treated water. The bottom and sides of the biofiltration system were sealed to prevent exfiltration to the surrounding soil, for the purpose of tracking the mass balance.

McDowall

The second field site was a small biofiltration basin in McDowall, Queensland (Fig. 2). This system was retrofitted into the streetscape of a residential area in 2006. The 20 m^2 treatment area (2% of the impervious catchment area) contained a 400 mm deep sandy loam filter media and a dense growth of various *Dianella* species. Following plant establishment difficulties, the central section of the biofilter was replanted with *C. appressa* in early 2007. Road runoff was diverted into the biofilter, where an overflow

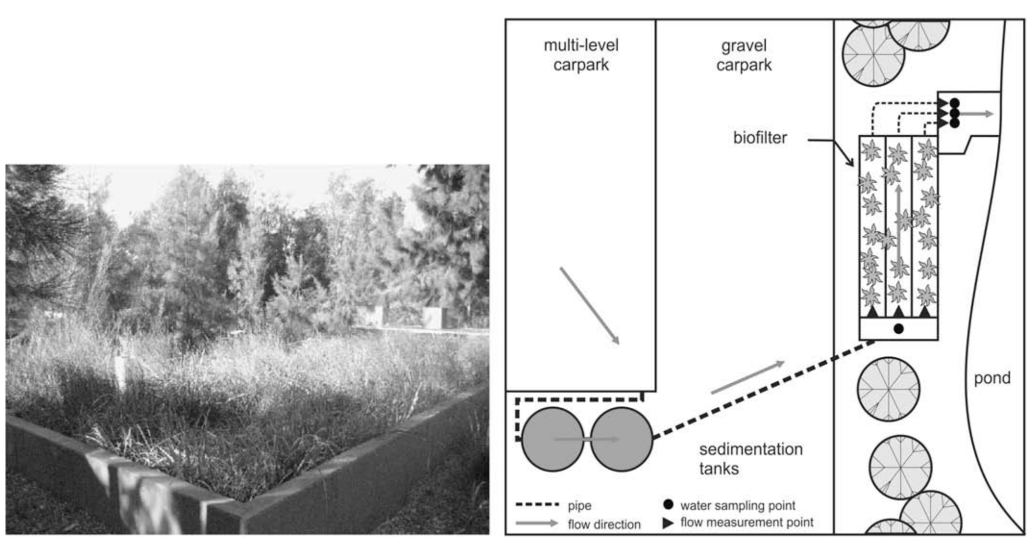

Fig. 1. Monash University, Melbourne, June 2007.

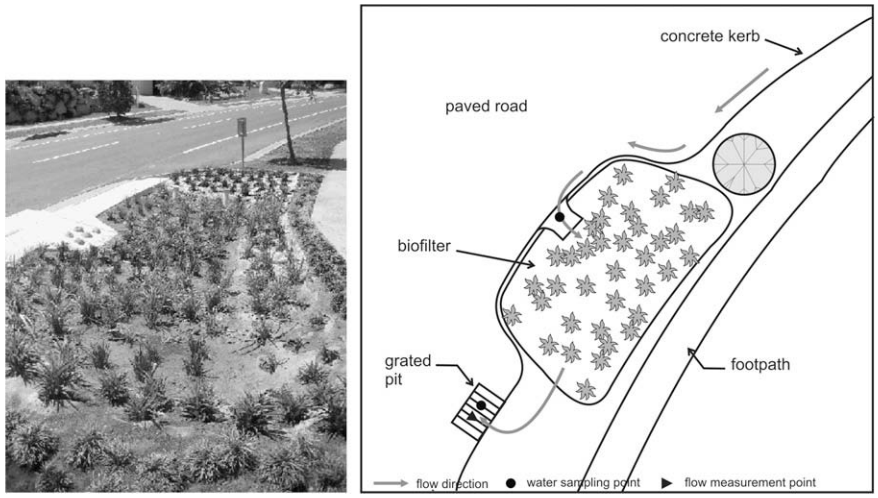

Fig. 2. McDowall, Brisbane, October 2006.

drain allowed a maximum ponding depth of 200 mm. Two perforated 100 mm diameter PVC underdrain pipes in the underlying drainage layer (100 mm sand plus 200 mm gravel) conveyed the treated water to a side-entry pit, which connected to the existing storm drainage system.

Bracken Ridge

A third biofiltration basin, at Bracken Ridge, Queensland, was also monitored (Fig. 3). This system was installed in 2001 to treat runoff from a 1.74 ha catchment, made up of three road sub-catchments. The filter media consisted of a 50 mm covering of shredded hardwood mulch, 400 mm sandy loam, 250 mm sand, and a 200 mm gravel drainage layer. A layer of geotextile separated the sand and gravel layers. A 150 mm slotted agricultural (Ag) pipe wrapped in geotextile was placed in the drainage layer, spaced approximately every 2 m across the media surface area. The 860 m^2 treatment area (5% of the catchment area) was vegetated with *L. longifolia* and *Melaleuca quinquinerva*.

Data collection

Monash University

Flows and water quality were monitored at the Monash University site from December 2006 to May 2007. Levelled V-notch weirs and ultrasonic depth sensors (Siemens Miltronics) were used to continuously (1 min time step) monitor flow rates, while autosamplers (Sigma 900) collected flow-weighted water quality samples at the inlet and from the outlet of each of the three cells during storm events. The accuracy of the flow measurements was regulary checked using manual flow measurements i.e., zero was checked and ultrasonic level monitors adjusted accordingly. It is believed that the uncertainty in the flow measurements at this site is well below the 10% that is standard in stormwater monitoring practice (Fletcher and Deletic, 2007). Water quality samples were collected within 24 h of each storm event and analysed for total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), filterable reactive phosphorus (FRP), ammonium (NH_4^+), nitrate/nitrite (NO_x), dissolved organic nitrogen (DON), particulate organic nitrogen (PON), copper (Cu), cadmium (Cd), lead (Pb), zinc (Zn), and manganese (Mn). Event mean concentrations (EMCs) were measured (composite samples) for most events, but for some all samples were analysed to obtain a complete pollutograph. Analyses were undertaken by the NATA-accredited (URL http://www.nata.asn.au) Water Studies Centre analytical laboratory, using standard methods and quality assurance/control procedures (APHA/AWWA/WPCF, 1998; Hosomi and Sudo, 1986). Uncertainties in TSS concentrations have previously been reported as approximately 30% for general stormwater monitoring

Fig. 3. Bracken Ridge, Brisbane, August 2003.

(Bertrand-Krajewski and Bardin, 2002), while a recent study of stormwater *Escherichia* coli levels (a particulate-associated pollutant) found a similar level of uncertainty (McCarthy et al., 2008). Given the experimental procedure followed in this study, it is reasonable to assume that the associated uncertainty is likely to be less than 30% at all sites. Further, it is estimated that the measurement accuracy for the other measured pollutants will be even better, particularly for dissolved constituents.

The infiltration capacity was monitored over a period of 18 months to investigate the impacts of compaction, clogging, and vegetation on hydraulic performance. On seven occasions the system was flooded for at least 24 h (until steady-state outflow was reached) by maintaining a constant water level of 250 mm (using water from the adjacent pond, Fig. 1). Saturated hydraulic conductivity (K_s) was then calculated using Darcy's Law.

McDowall

Four simulated storm experiments were conducted at the McDowall site, in October 2006 (before the *Dianella* died off), June 2007 (several months after replanting with *C. appressa*), and two in October 2007 (on consecutive days). De-chlorinated tap water was used to prepare semi-synthetic stormwater according to the method described by Hatt et al. (2007c), targeting 'average' pollutant concentrations as follows: TSS, 150 mg/L; TN, 1.69 mg/L; NO_x, 0.59 mg/L; NH_4^+, 0.24 mg/L; DON, 0.47 mg/L; PON, 0.39 mg/L; TP, 0.31 mg/L; Cd, 0.0045 mg/L, Cu, 0.05 mg/L; Pb, 0.14 mg/L; and Zn, 0.25 mg/L (Duncan, 2006). The semi-synthetic stormwater was then applied at a volume and rate equivalent to a 3-month Average Recurrence Interval (ARI) storm event for the catchment's critical duration (3000 L over 15 min). This recurrence interval was chosen as it reflects the design storm for which the system was designed. The stormwater mix was continuously stirred during the application period to ensure constant pollutant concentrations, therefore only one composite inflow sample was taken. Effluent flow was measured manually (using a stop-watch and measuring cylinder) at 5 min intervals; this extended to 10 min intervals once the peak had passed and flows stabilised (approximately 90 min after inundation). This method of flow measurement has a high level of accuracy i.e., an uncertainty of far less than 10%. Flow appeared at the outlet 20–30 min after application, and water quality samples were collected at approximately 150 L intervals thereafter. Water quality variables measured in all samples were TSS, TP, TN, FRP, NH_4^+, NO_x, DON, PON, Cu, Cd, Pb, and Zn.

Bracken Ridge

The Bracken Ridge site was monitored from December 2005–March 2006. Autosamplers (Sigma 900 Max) were used to collect time-weighted water quality samples from each of the three inlets and from the outlet. All collected water quality samples were analysed for TSS, TP, TN, FRP, NH_4^+, NO_x, Cu, and Zn. Analysis of the water quality samples collected at this site and the McDowall site was undertaken by the NATA-accredited Brisbane Water Scientific Analytical Services facility using standard methods and quality assurance/control procedures. Although flow rates were also measured continuously at all three inlets and outlet, it was found that records were not accurate and so the flow data could not be used, thus precluding any hydrologic or loads analysis at this site.

Data analysis

Hydrologic assessment

In order to assess the potential of biofilters for reducing the volume and frequency of runoff, inflow and outflow volumes were estimated as the integral of the measured flows over time. Changes in peak flows were also assessed. At the Monash University site, an event was defined as the period during which flows exceeded the detection limit of the instrumentation (0.01 L/s), while at the McDowall site each event extended to 24 h after the beginning of the simulation. The proportion of the inflow volume that passed through each cell at the Monash University site could not be calculated because there was one extended detention zone rather than three separate zones (one above each cell). Therefore, the volumes from the three outlets were summed to give a total outflow volume, and so the hydrologic performance of this biofilter was assessed as a whole, rather than as three individual cells.

The losses (volume of retained water by the biofilter) and peak flow reductions were analysed further for Monash University biofilter only. An attempt was made to relate these variables to the storm event size and intensity (rainfall intensity averaged across the event, event duration, inflow volume) and seasonal influences (date, antecedent dry weather period – ADWP). The relationships between losses, flow reductions and the five predictor variables were assessed using multiple linear regression. The distribution of the datasets were checked for normality using Kolmogorov–Smirnov tests (significance accepted at $p > 0.1$) prior to using hierarchical regression analysis to determine the proportion of variance explained by each variable.

Pollutant concentrations

For each of the three sites, Kolmogorov–Smirnov tests ($p > 0.1$) were used to check that the distribution of the data approximated normality, and data were transformed where required. Pearson correlation coefficients (R) were calculated to evaluate the relationship between stormwater and effluent pollutant concentrations and flow. Where time-series data were collected, pollutographs (plots of pollutant concentrations against time) were constructed to assess the relationship between flow, time, and pollutant concentrations. Boxplots were created to compare the range of stormwater and effluent concentrations at each sampling point at the Monash University (EMC data) and Bracken Ridge (pollutograph data) sites.

Pollutant loads

Pollutant loads over the duration of a storm event were estimated for each sampling point as the integral of the product of measured flows and concentrations over time. The uncertainty in measured volumes was assessed for the McDowall site (following the methodology described by McCarthy et al., 2008) as between 1% and 3% for the four storm simulations (when flow uncertainty was overestimated as 10%). Since flow at the Monash University site was measured using a substantially higher number of points in time and had a flow uncertainty of less than 10%, the volumetric accuracy at this site should be of a similar, if not higher, level than that estimated for the McDowall site. Therefore, the level of uncertainty in loads is believed to be less than 10% for TSS (Fletcher and Deletic, 2007) and even lower for other pollutants. Since the proportion of inflow that passed through each cell at Monash University could not be calculated, it was assumed that one third of the flow passed through each cell; the loads from the three outlets were then summed to give a total load out. This approach is reasonable, given that the Monash system had inlet weirs set at identical levels, fed by a large stilling basin designed to maximise the uniformity of flows over the three weirs.

Results

Hydrologic performance

Monash University

During the monitoring period, flow data were collected for 28 storm events. However, the high-flow bypass was engaged during

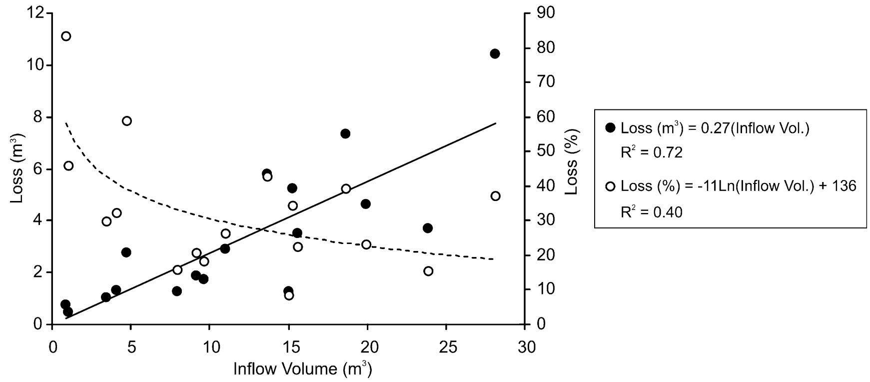

Fig. 4. Relationship between volumetric loss (closed circles, solid regression line) and proportional loss (open circles, dashed regression line) and inflow volume at Monash University.

11 of these events; the bypass weir was not rated, therefore overflow volumes were unknown and flow data for these events were excluded from the hydrologic performance analysis. This means that more than one third of events overflowed, indicating that the system is very small for its catchment.

On average, 33% of the inflow volume was retained by the biofilter (range: 15–83%). The total volume lost is clearly proportional to the inflow volume, with losses increasing with inflow volume (Fig. 4). Not surprisingly, the proportional loss decreases non-linearly with increases in inflow volume. The five predictor variables jointly explained 79% of the total variance in losses, however inflow volume alone explained 72% of the variance in volumetric losses. This suggests that losses could be modelled using inflow volume as the sole predictor variable. However, this finding should be taken with great caution, since only small to moderate events were used in the analysis (because the larger events overflowed). It is very likely that the relationship would not be linear if all events could be included (i.e., it is suggested that losses would reach a maximum value and would not increase with a further increase in inflows) and that the influence of the ADWP would be more important for larger storms, where filter media saturation is reached.

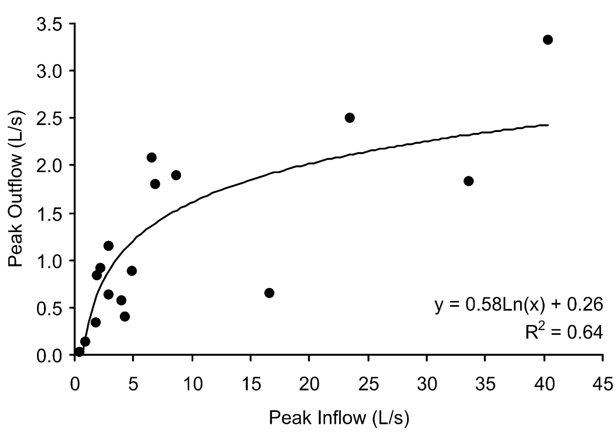

Fig. 5. Relationship between peak inflows and outflows at the Monash University site.

Table 1
Total volumes and losses for the McDowall biofilter during four simulated storm events.

Simulation	Inflow (L)	Outflow (L)	Loss (L)	ADWP (days)	Peak Q_{out}	
					(L/s)	(as a% of mean Q_{in})
25 October 2006	3000	2593	407 (14%)	3	0.48	14
19 June 2007	3000	2097	903 (30%)	11	0.48	14
23 October 2007	3000	2226	774 (26%)	12	0.66	20
24 October 2007	3000	2670	330 (11%)	0	0.50	15

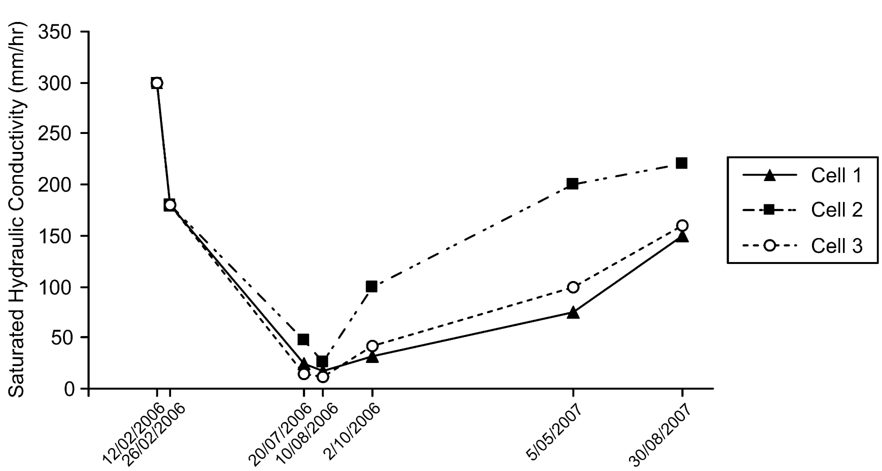

Fig. 6. Evolution of saturated hydraulic conductivity at the Monash University site.

An attempt was made to calculate the maximum percentage of water lost during the monitoring period, as well as the proportion of water treated. To do this, losses during the events that overflowed had to be estimated. This was done by assuming that the volumetric relationship shown in Fig. 4 could be extrapolated for events with inflows greater than 30 m^3 (this gives an overestimate of performance). These calculations revealed that total losses over six months are 27% while 73% of water was treated by the system during this time.

The mean peak flow rate reduction was 80% (range: 37–96%). There is a clear relationship between peak inflow and outflow rates (Fig. 5). Of the five predictor variables, the peak outflow rate was most strongly correlated with peak inflow rate and inflow volume ($R^2 = 0.72$, compared to 0.80 for the full model).

Immediately following completion of construction, the saturated hydraulic conductivity of all three filter media was estimated to be around 300 mm/h (Fig. 6). Within two weeks, this had reduced to around 180 mm/h (the design value). Following this, the

Table 2

Mean values ± standard deviation of each pollutant in stormwater and the effluent of the three cells for three discretely sampled rain events at Monash University. Pearson correlation coefficients (*R*) indicate relationship between pollutant concentrations and flow are also shown.

	Concentration (mg/L)				*R*			
	Stormwater ($n = 31$)	Effluent			Stormwater	Effluent		
		Cell 1 ($n = 35$)	Cell 2 ($n = 38$)	Cell 3 ($n = 37$)		Cell 1	Cell 2	Cell 3
TSS	39 ± 62	5 ± 6	3 ± 5	4 ± 6	**0.59**[**,a]	**0.42**[*]	**0.50**[**,a]	**0.57**[**,a]
TP	0.07 ± 0.08	0.22 ± 0.08	0.16 ± 0.06	0.17 ± 0.08	**0.57**[**,a]	**0.37**[*,a]	**0.42**[**,a]	**0.40**[*]
FRP	0.006 ± 0.004	0.11 ± 0.03	0.11 ± 0.04	0.10 ± 0.04	0.25[c]	**0.44**[b]	**0.50**[b]	**0.33**[a]
TN	1.1 ± 0.5	1.3 ± 0.3	1.1 ± 0.4	1.3 ± 0.6	**0.47**[**]	**0.35**[*]	**0.48**[**]	**0.55**[**,a]
NO_x	0.4 ± 0.2	0.3 ± 0.2	0.3 ± 0.3	0.14 ± 0.09	0.34	0.22	0.17	0.21
NH_4^+	0.04 ± 0.06	0.03 ± 0.01	0.02 ± 0.01	0.03 ± 0.02	0.15	**0.36**[a]	**0.44**[b]	**0.50**[b]
DON	0.3 ± 0.3	0.8 ± 0.2	0.6 ± 0.3	0.8 ± 0.4	−0.19	0.28	**0.61**[**]	**0.50**[**]
PON	0.3 ± 0.3	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.2	**0.55**[**,a]	0.19[a]	0.11	0.18[a]
Cu	0.01 ± 0.1	0.006 ± 0.002	0.006 ± 0.002	0.004 ± 0.002	**0.46**[**,a]	0.12	**0.65**[**]	**0.61**[**]
Mn	0.02 ± 0.02	0.008 ± 0.006	0.004 ± 0.008	0.02 ± 0.03	**0.53**[**]	0.12[a]	0.31	−0.07
Pb	0.006 ± 0.003	0.002 ± 0.002	0.002 ± 0.001	0.003 ± 0.001	0.47	−0.51[a]	0.03	0.19
Zn	0.1 ± 0.2	0.03 ± 0.02	0.015 ± 0.007	0.013 ± 0.004	0.11[a]	−0.41[a]	**0.44**[**,a]	−0.13

Significant correlations are shown in bold type.

[*] $p < 0.05$.

[**] $p < 0.01$.

[a] Log-transformed.

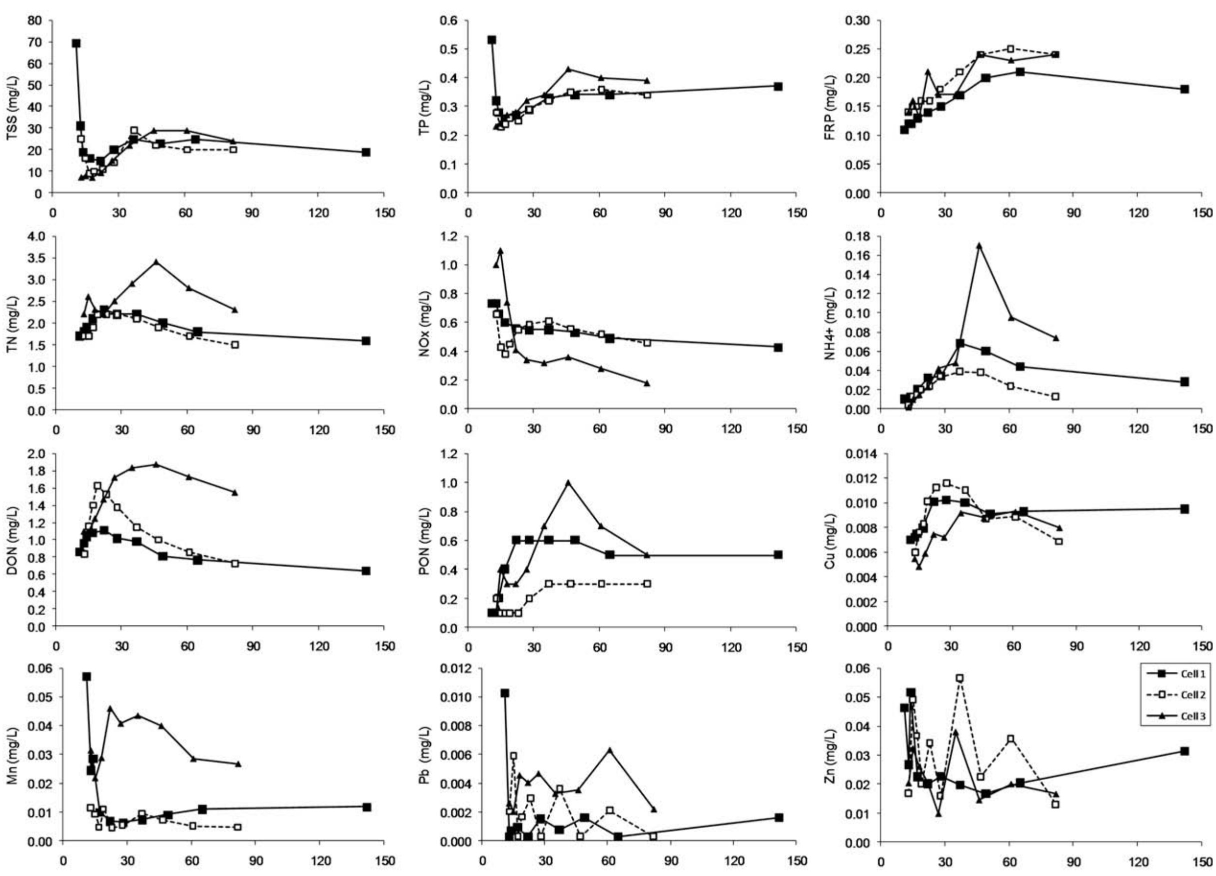

Fig. 7. Effluent for one storm event at the Monash University site. Data are representative of all three discretely sampled storm events at this site.

infiltration capacity dropped to far below the design specification (July–August 2006, Fig. 6). It is hypothesised that this was due to compaction of the filter media under hydraulic loading and a dense layer of moss growing on the surface of the biofilter (the result of placing a "hothouse" over the biofilter during the first winter, to accelerate plant growth). Removal of the moss layer improved the hydraulic conductivity, particularly for the SLVP media (Cell 2, October 2006, Fig. 6). Further significant increases in infiltration capacity coincided with vigorous vegetation growth, indicating that the root zone of vegetation also has an important role to play in maintaining the porosity of the filter media (Archer et al., 2002). This trend is consistent with results observed in a laboratory study in CiCheng, China (Wong, Personal Communication, 2007).

McDowall

Although the inflow volume for all storm simulations conducted at the McDowall site were equal, the total outflow volumes varied substantially, taking into consideration the associated uncertainty (Table 1). Here, it appears that the ADWP influenced losses (Table 1), although this can only be tentatively hypothesised with only four samples. The relative peak flow reductions were consistent with those observed at the Monash site (Table 1).

Treatment performance

Effluent concentrations

Monash University. During the monitoring period, water quality data were collected for 14 storm events; flow-weighted EMCs were measured for all 14 events, and pollutographs for three events (each containing from 7 to 16 discrete samples). Concentrations of Cd were nearly always below the detectable limit in both the incoming stormwater and effluent from all three outlets and are not reported.

In general, very few differences in the pollutant removal performance of the three filter media types were observed during each of the three discretely sampled storms (Table 2, Fig. 7). Concentrations of sediment and heavy metals were consistently reduced (Table 2). Effluent concentrations of phosphorus were always higher than influent levels and also increased with flow rate; this was driven by leaching of dissolved phosphorus (Table 2). Concentrations of all forms of nitrogen in the effluent were largely unchanged relative to the incoming stormwater.

It was therefore not surprising that the calculated Pearson correlation coefficients revealed that stormwater concentrations of TSS, TP, TN, PON, Cu, and Mn were all moderately correlated to flow, however this was not the case for dissolved nutrients, Pb or Zn (Table 2). There were moderate correlations of flow with efflu-

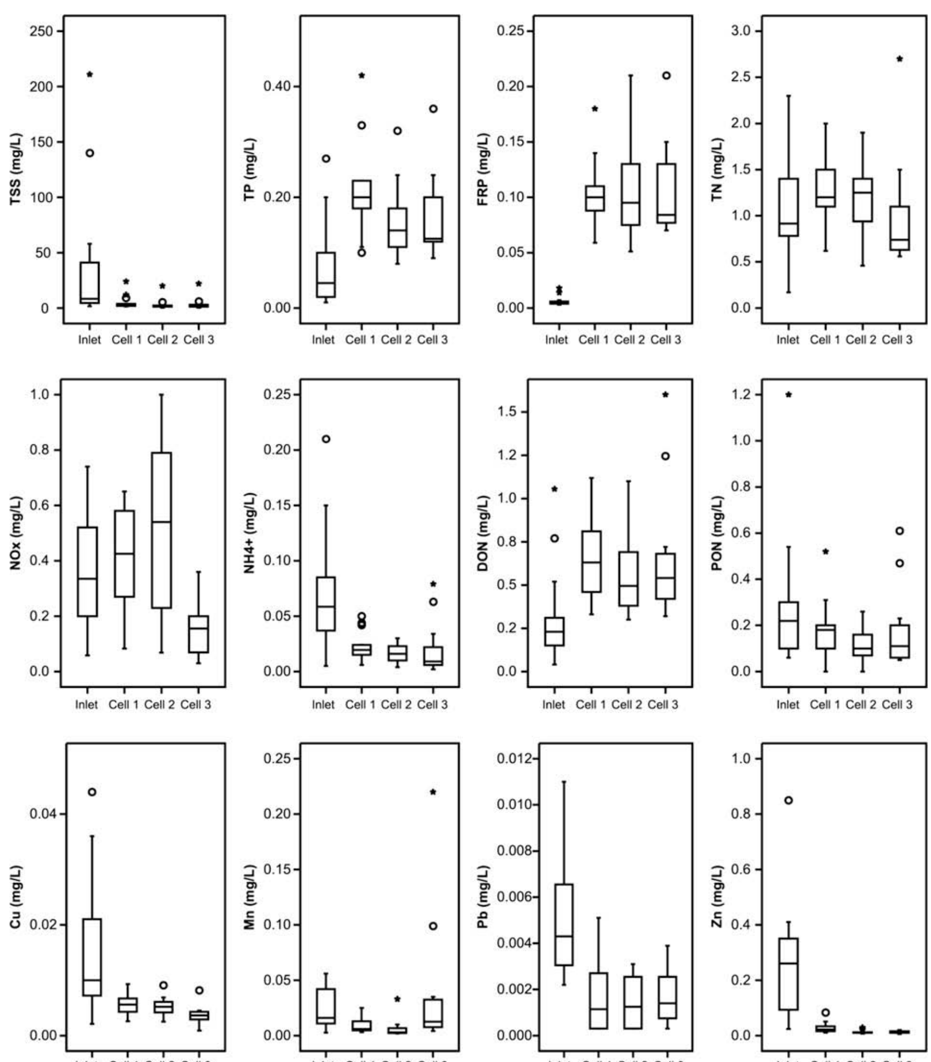

Fig. 8. Range of pollutant EMCs for 14 rain events at the Monash University site.

ent concentrations of TSS, TP, TN, NH_4^+, and FRP from all three cells, and with concentrations of DON, Cu, and Zn from at least one cell (Table 2).

Not surprisingly, EMCs followed the same trends as those observed during the discretely sampled events (Fig. 8). For the pollutants that were well retained, the reliability of treatment is evident, with a narrow range of low effluent concentrations relative to the influent stormwater. These results also demonstrated that NO_x concentrations were consistently reduced in Cell 3 (Fig. 8). While NH_4^+ and peak TN concentrations were also reduced, this was countered by consistent leaching of DON (Fig. 8), the result being neglible change in concentrations of TN.

Interestingly, there was a clear influence of seasonality on NO_x concentrations in Cells 1 and 2, with effluent NO_x concentrations increasing as the season progressed from mid-summer to late autumn (Cell 1, $R^2 = 0.44$; Cell 2, $R^2 = 0.62$). Similarly, effluent NO_x concentrations from Cell 3 increased with the ADWP ($R^2 = 0.53$). This latter observation is consistent with the results of a study of non-vegetated filters conducted by Hatt et al. (2007a). It is hypothesised that seasonality and ADWP are surrogates for temperature and moisture, respectively, and that a decrease in either of these latter parameters will lead to a decreased biological processing of nitrogen.

Table 3
Pollutant concentrations (mean ± standard deviation) for four stormwater simulations at McDowall. Pearson correlation coefficients (*R*) indicate the relationship between effluent pollutant concentrations and flow. Concentrations for heavy metals were largely below the detectable limit, hence maximum values only are reported and correlations for these parameters were not determined.

	Concentration (mg/L)		*R*
	Stormwater (*n* = 4)	Effluent (*n* = 59)	
TSS	128 ± 32	14 ± 19	$0.49^{**,a}$
TP	0.4 ± 0.3	0.07 ± 0.06	$0.34^{**,a}$
FRP	0.1 ± 0.2	0.01 ± 0.01	$-0.39^{**,a}$
TN	2.7 ± 0.2	2.2 ± 0.7	0.34^{**}
NO_x	1.0 ± 0.2	1.6 ± 0.7	0.26^{*}
NH_4^+	0.5 ± 0.2	0.02 ± 0.03	0.14
DON	0.9 ± 0.2	0.5 ± 0.2	0.11
PON	0.4 ± 0.1	0.1 ± 0.1	0.01
Cd	0.005 ± 0.001	<0.001[b]	–
Cu	0.06 ± 0.01	0.005[b]	–
Pb	0.11 ± 0.02	0.007[b]	–
Zn	0.33 ± 0.06	0.013[b]	–

Significant correlations are shown in bold type.
* $p < 0.05$.
** $p < 0.01$.
[a] Log-transformed.
[b] Maximum concentration.

McDowall

Comparison of effluent concentrations to the applied stormwater during the four storm simulations showed substantial reductions of TSS, TP, FRP, NH_4^+, DON, Cd, Cu, Pb, and Zn (Table 3). TN and NO_x effluent concentrations were largely equal to or greater than influent concentrations. PON was leached early in the hydrograph (Fig. 9), however overall concentrations were reduced. While there was little between-experiment variation in effluent concentrations of suspended solids, phosphorus, and heavy metals, there was notable variation in effluent concentrations of TN, NO_x, and NH_4^+ (Fig. 9).

Effluent concentrations of TSS, TP, TN, and NO_x all clearly exhibit pollutograph behaviour (Fig. 9). Flow was moderately correlated with TSS, TP, FRP, TN, and NO_x (Table 3). It is possible that

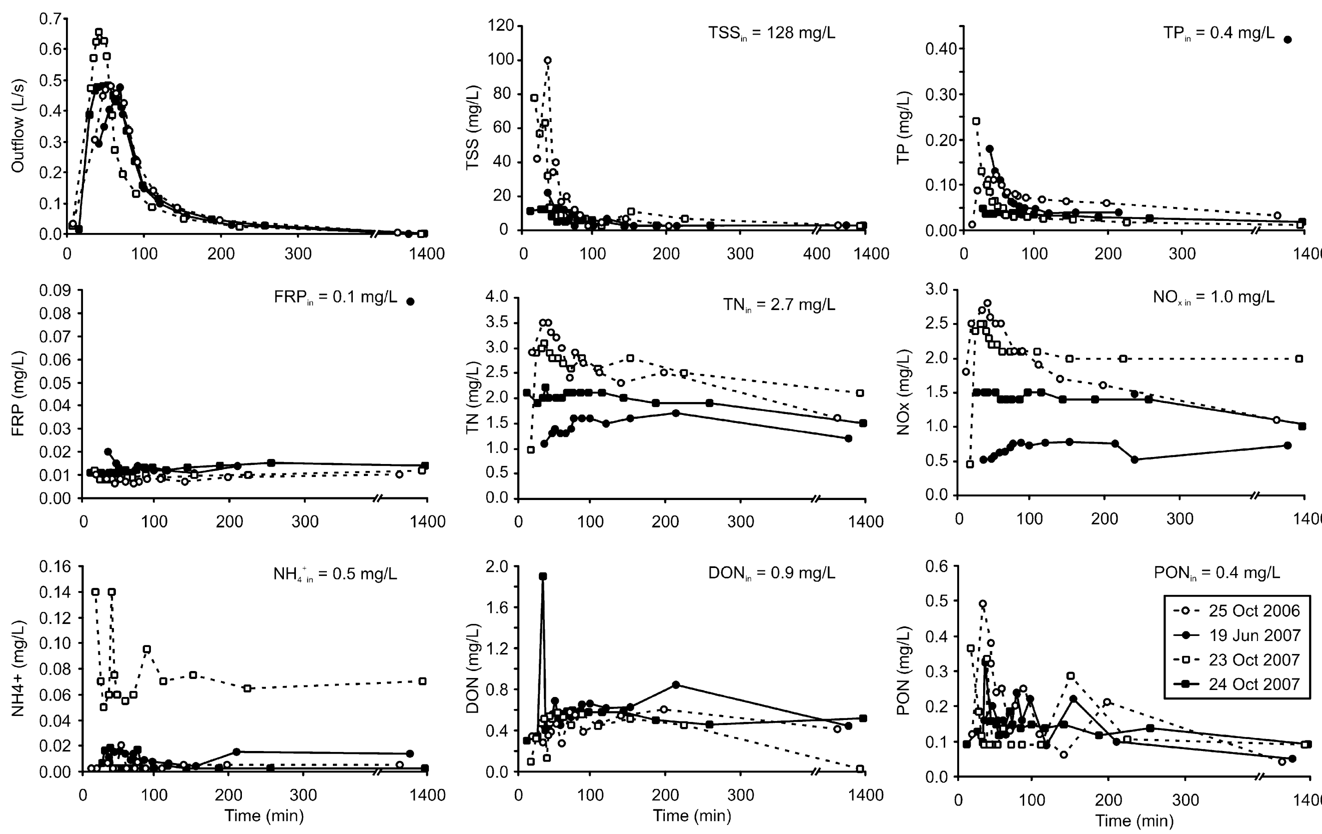

Fig. 9. Effluent pollutographs for four storm simulations conducted at the McDowall site (mean influent pollutant concentrations are shown in the legend). Heavy metals are not shown because outflow concentrations were mostly at or below the detection limit.

the negative correlation between flow and concentrations of FRP was due to dissolution dynamics; where flow is high, water rapidly passes through the media profile, hence there is less opportunity for dissolution to occur. However, there is also evidence for "first flush" behaviour in concentration, where FRP, TN, and NO_x stored in the filter media are mobilised by the wetting front (Fig. 9).

Bracken Ridge. Water quality data were collected for nine storm events during the monitoring period (December 2005 to March 2006). Stormwater concentrations of TSS, Cu, and Zn were highest at the start of each event (Fig. 10) and are likely to follow the hydrograph (although the magnitude of the measured flow rates was not reliable, the shape of the hydrograph was generally well recorded). Patterns in nutrient concentrations in the incoming stormwater were more variable and did not follow any clear trend.

Despite variation in inflow concentrations, pollutant concentrations in the effluent were relatively constant (Fig. 10), although an initial spike was sometimes observed for TP, TN, Cu, and Zn. It can be seen that the range of effluent pollutant concentrations is narrow compared to stormwater concentrations (Fig. 11), suggesting a level of reliability in treatment.

Pollutant loads

Monash University. Pollutant loads were calculated for seven storm events (events where the high-flow bypass was engaged were excluded). The change in loads was generally highly variable, particularly for nutrients (Table 4). The large observed variation in load reductions is a product of the variation in effluent concentrations (Fig. 8) as well as the variation in losses (which is determined by the size of the storm event, the ADWP and seasonality) and is therefore not entirely surprising. Loads of TSS, NH_4^+, PON, and heavy metals were fairly consistently reduced, with variability largely caused by variations in inflow concentration (given the innate mathematical dependence of reductions on the inflow concentration). However, elevated effluent concentrations of TP, FRP, TN, and DON generally resulted in export of nutrients from the system. Although the mean NO_x load reduction is negative (Table 4), moderate reductions (33–78%) were observed from January to April, suggesting that greater denitrification is occurring in warmer months, particularly in Cell 3, where reductions in NO_x concentrations were most marked. However, this trend reversed as daily temperatures decreased, resulting in a net export of NO_x.

McDowall. Reduced pollutant concentrations and flow volumes resulted in very high removals of sediment, phosphorus, NH_4^+, and heavy metals, and moderate DON load reductions during all storm simulations (Table 4). In contrast, nitrogen removal was more variable. Reductions in loads of TN were influenced by variable removal (or leaching) of NO_x and to some extent DON. Retention of loads of PON notably improved after the first experiment, presumably because less particulate matter was washed from the biofilter.

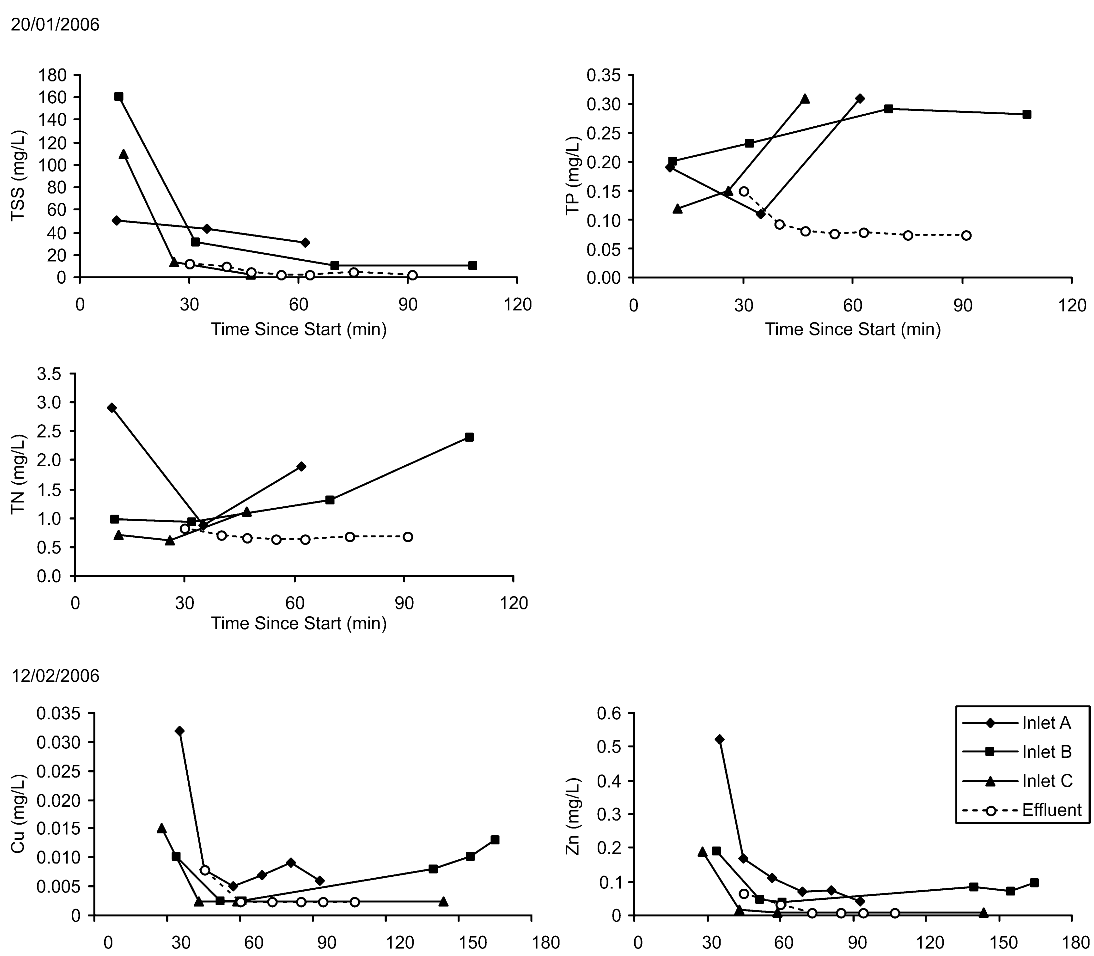

Fig. 10. Time-series pollutant concentrations for two storm events at Bracken Ridge. Data most representative of general trends are shown.

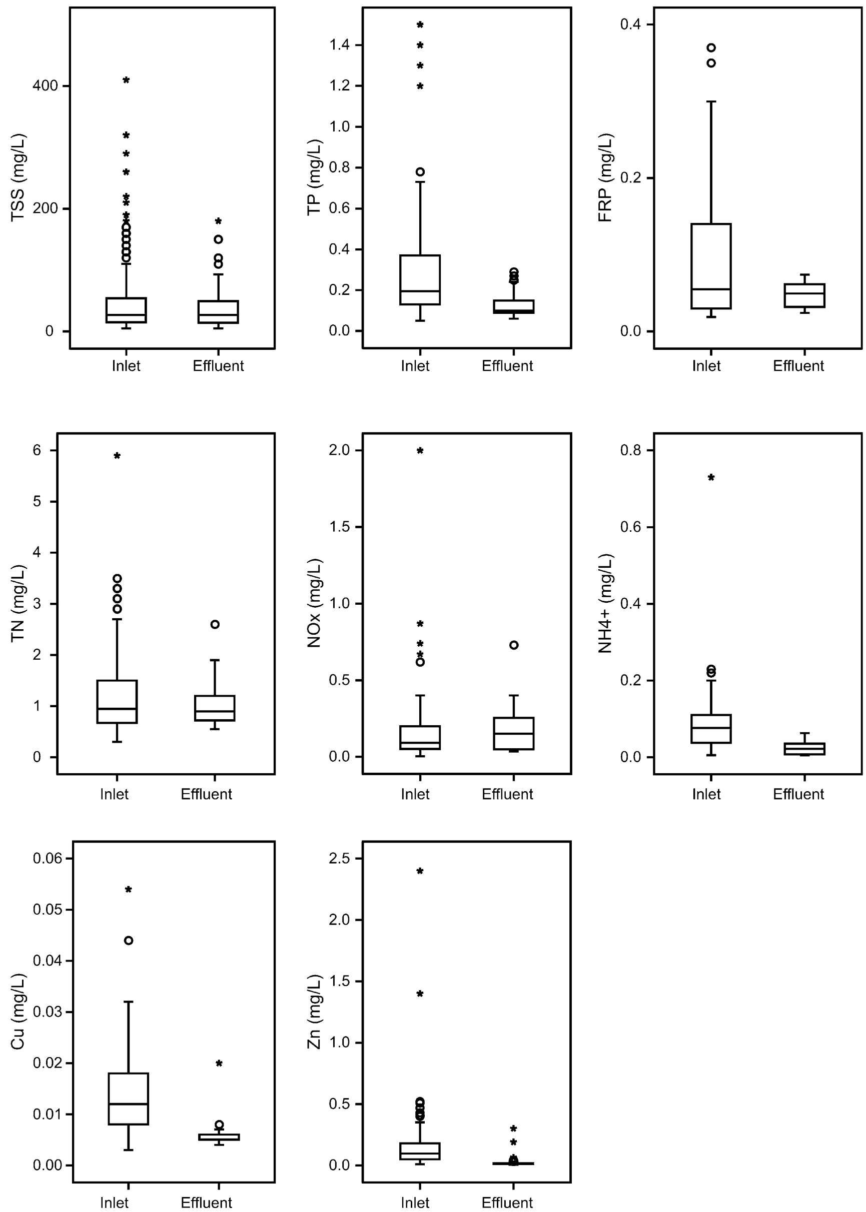

Fig. 11. Range of pollutant concentrations at Bracken Ridge.

Discussion

Hydrologic performance

Both the Monash University and McDowall biofiltration systems substantially reduced total runoff volumes and flow peaks. This has important implications for management of urban waterways, where increased flows are a key stressor (Paul and Meyer, 2001). The reduction in peaks is also particularly important for managing stormwater systems in existing areas that are subject to urban densification. Little reduction in the frequency of discharge was observed at the Monash University site, where only very small storm events were completely intercepted. However, this biofilter is only 1% of the impervious catchment area, substantially smaller than the typical 2% used in practice (Melbourne Water, 2005). It is therefore reasonable to expect that larger systems (relative to the contributing catchment area) would be able intercept larger events and thus make a higher contribution to reducing both runoff frequency and volume (i.e., increased actual and proportional losses).

There does not appear to be any seasonal influence on losses at the Monash University site. This is somewhat surprising, in that it might be expected that evapotranspiration would be higher in warmer months, as was observed by Hunt (2003) in his field study of a biofilter. However, monitoring of the Monash University site was only over summer and autumn, and analyses included only small-medium events where the influence of inflow volume was overwhelming. Continued monitoring will allow better assessment of seasonality.

Treatment performance

The three biofiltration systems studied effectively and consistently reduced concentrations of TSS and heavy metals, but the reduction of nutrient concentrations is highly variable. Given the particle size distribution of the filter media at all sites and colour differences between the influent and effluent, any sediment and heavy metals in the effluent are most probably fine media particles that have washed out. This is consistent with observations made by Hsieh and Davis (2005) in their study of eight biofiltration systems.

Table 4
Pollutant removal performance summary (mean ± standard deviation) for seven events at Monash University and four storm simulations at McDowall.

	Load reduction (%)	
	Monash University	McDowall
TSS	76 ± 25	93 ± 4
TP	−398 ± 559	86 ± 3
FRP	−1271 ± 1067	81 ± 15
TN	−7 ± 72	37 ± 21
NO_x	−13 ± 93	−17 ± 35
NH_4^+	64 ± 42	96 ± 7
DON	−129 ± 232	58 ± 11
PON	38 ± 55	79 ± 12
Cd	–	91 ± 2
Cu	67 ± 23	98 ± 1
Mn	38 ± 53	–
Pb	80 ± 15	98 ± 0.5
Zn	84 ± 26	99 ± 0.1

Leaching of phosphorous from the Monash University biofilter may be attributable to the phosphorus content of the filter media. In a related, laboratory-scale column study, the phosphorus and organic matter content of the filter media was substantially lower (e.g. 150 mg/kg TP compared to 380 mg/kg TP), and resulted in an at least 80% reduction of TP concentrations (Fletcher et al., 2007). Interestingly, Hsieh and Davis (2005) observed a positive correlation between organic matter content and TP removal, where the filter media contained up to 280 mg/kg TP but only 2.1% organic matter (compared to 5% in the Monash University biofilter). Further, Phillips (1998) showed that soil containing organic carbon could retain large amounts of phosphorus. This may suggest that it is the form of phosphorus, rather than the absolute amount, that is important for leaching. Further research is clearly required before firm conclusions on what is triggering phosphorus leaching can be made. However, the practical implication of the findings could be that, since Australian plants tend to be adapted to low phosphorus conditions, the simple solution may be to minimise the amount (and all forms) of phosphorus in the filter media.

Removal of nitrogen and its species is even more interesting. In a large scale laboratory study, Read et al. (2008) found that both the presence and type of vegetation had an overwhelming influence on nitrogen removal in biofilters (this was confirmed by a parallel laboratory study conducted by Fletcher et al., 2007). This at least partially explains the improved nitrogen retention observed at McDowall when the *Dianella* spp. (which was shown by both laboratory studies to perform poorly) were replaced with *C. appressa* (shown to have a high nitrogen removal capacity).

It can be seen that, even where there is effective removal of organic nitrogen and NH_4^+, effluent NO_x concentrations are often unchanged relative to the influent stormwater. NO_x is highly soluble and does not sorb well, therefore removal is reliant on either plant uptake or removal via denitrification. Enabling a pathway for removal of NO_x is critical, since any incoming organic N that is retained by the biofilter will ultimately be converted to NO_x via mineralisation, ammonification and nitrification (although some will be taken up by plants) and, unless converted to N_2 gas by denitrification, will be subsequently leached (Davis et al., 2006). Laboratory-scale studies have successfully removed NO_x through the inclusion of a permanently submerged zone to create anoxic conditions (Kim et al., 2003; Zinger et al., 2007b). Moreover, this drainage configuration has been shown to be effective for countering the deleterious effects of extended dry periods on NO_x removal (Zinger et al., 2007a).

Like many other stormwater treatment technologies (Wong et al., 2006), biofilters appear to be capable of reducing pollutant concentrations down to an equilibrium or "background" concentration. This buffering effect is important for protecting the ecological health of receiving waters, by preventing pollution spikes. For pollutants whose primary removal processes are physical (sediment, heavy metals), this background concentration is determined by the amount of media particles washed out of the system and should therefore decrease as the system matures. Background concentrations for nutrients, on the other hand, will clearly be a function of the sorption capacity of the filter media and the processing capacity of the biological community (i.e., plant and microbial uptake, denitrification rates, etc.). Dietz and Clausen (2007) reported leaching of phosphorus from their biofilters, however their influent phosphorus concentrations are very low (mean TP concentration = 0.0015 mg/L), and possibly below the equilibrium concentration for that system. In the same vein, the situation may not be all that bad at the Monash University site, in that the high percentage export (i.e., negative load removal) of nutrients is a mathematical product of abnormally low influent concentrations. Further work to test the treatment performance of this biofilter with the sedimentation tanks offline, and so with higher inflow concentrations, is currently underway.

Design implications

Analysis of the hydrologic performance of biofilters suggests two implications. First, biofilters can attenuate flow peaks and reduce overall flow volumes, and so can play a role in restoring flow regimes closer to their pre-development levels (particularly where they can be built without lining, in order to promote exfiltration to surrounding soils). Second, where biofilters are used for stormwater harvesting, losses will need to be taken into account during the design phase, to ensure that water demands can be met.

In terms of treatment performance, a wide range of soil-based filter media will effectively remove TSS and heavy metals. However, in order to facilitate nutrient removal, use of a filter media with a low organic matter content (particularly phosphorus) and appropriate plant species may be the key design parameters. There are also a number of important considerations when designing for denitrification, and further work to test the performance of the Monash University biofilter with a permanently submerged zone that is currently underway should better inform this.

Finally, the influence of flow rates on effluent concentrations must also be taken into account when designing a biofiltration system. On the surface, it follows that selecting a filter media with a high hydraulic capacity will enable either treatment of a higher percentage of the mean annual flow or construction of a smaller sized system. However, the pollutograph data presented here suggests that higher infiltration rates may lead to higher effluent concentrations of particulates (and their associated pollutants). Thus, there appears to be a trade-off between hydraulic capacity and pollutant removal. Ultimately, the design of each biofiltration system will depend on site constraints and the target pollutants.

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